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(54) **BATTERY-FREE UNMANNED AERIAL VEHICLE**

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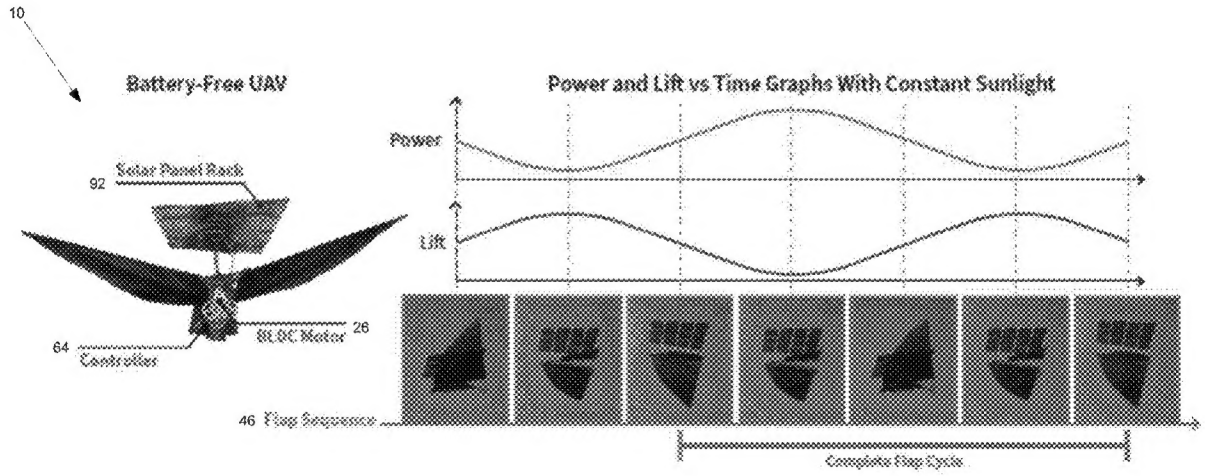
(57) **ABSTRACT**

Unmanned aerial vehicles are provided. In one aspect, the unmanned aerial vehicle includes a four-bar linkage mechanism in mechanical communication with a pair of wings. An electrical subsystem includes an actuator in mechanical communication with the four-bar-linkage mechanism. The actuator is in electrical communication with a capacitor. A plurality of solar panels is in electrical communication with the capacitor, which is configured to harvest non-battery energy from the plurality of solar panels to power the actuator for controlling the four-bar linkage mechanism to operate the pair of wings.



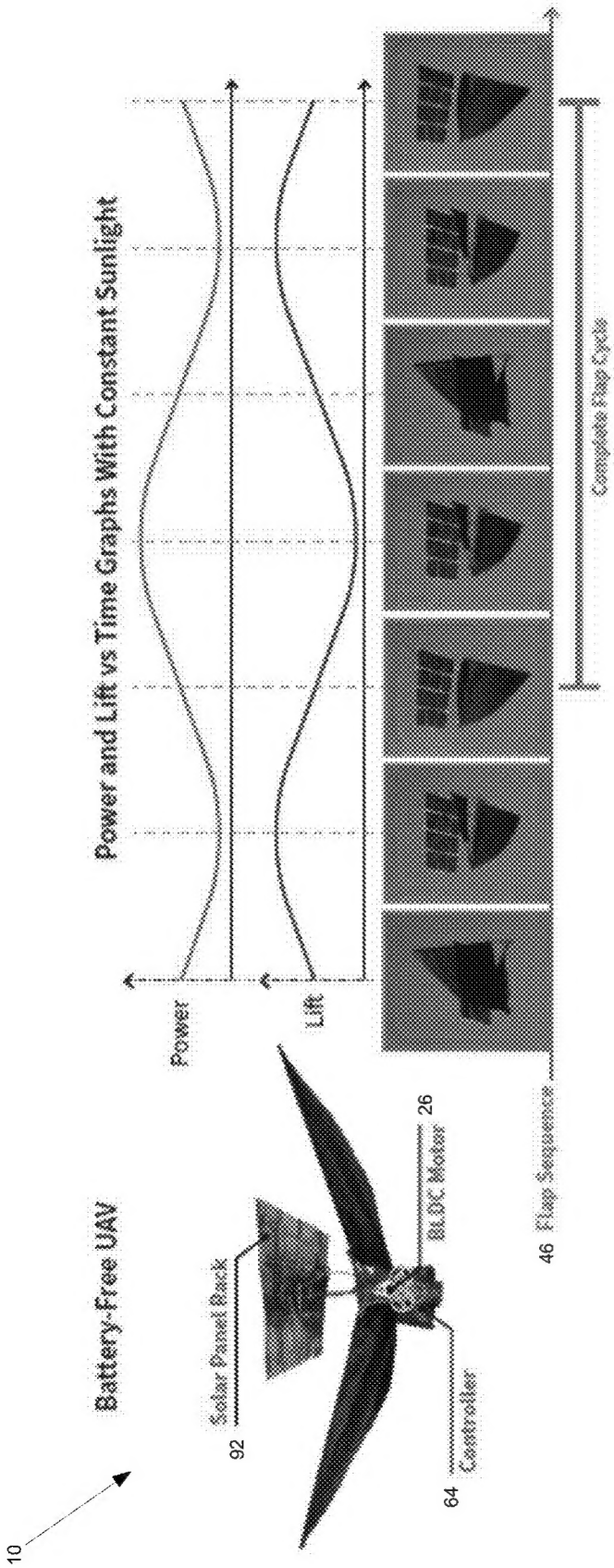

Battery-Free UAV
10
Solar Panel Rack
92
Controller
64
BLDC Motor
26
Flap Sequence
46
Power and Lift vs Time Graphs With Constant Sunlight
Power
Lift
Complete Flap Cycle

FIG. 1

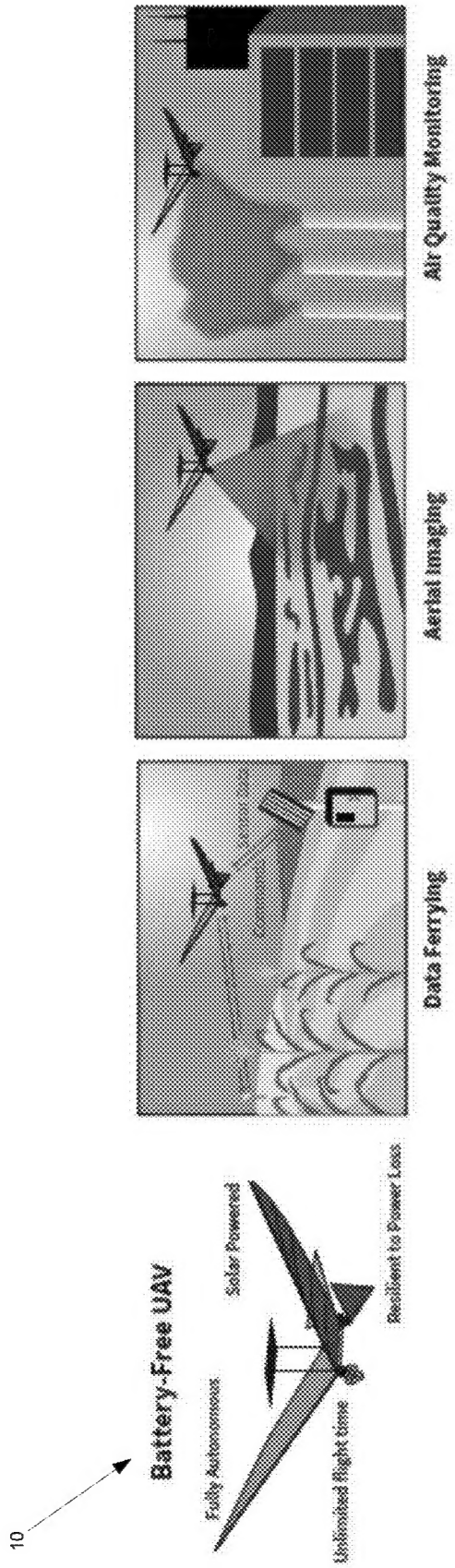

10
Battery-Free UAV
Fully Autonomous
Solar Powered
Unlimited Flight time
Resilient to Power Loss
Data Ferrying
Aerial Imaging
Air Quality Monitoring

FIG. 2

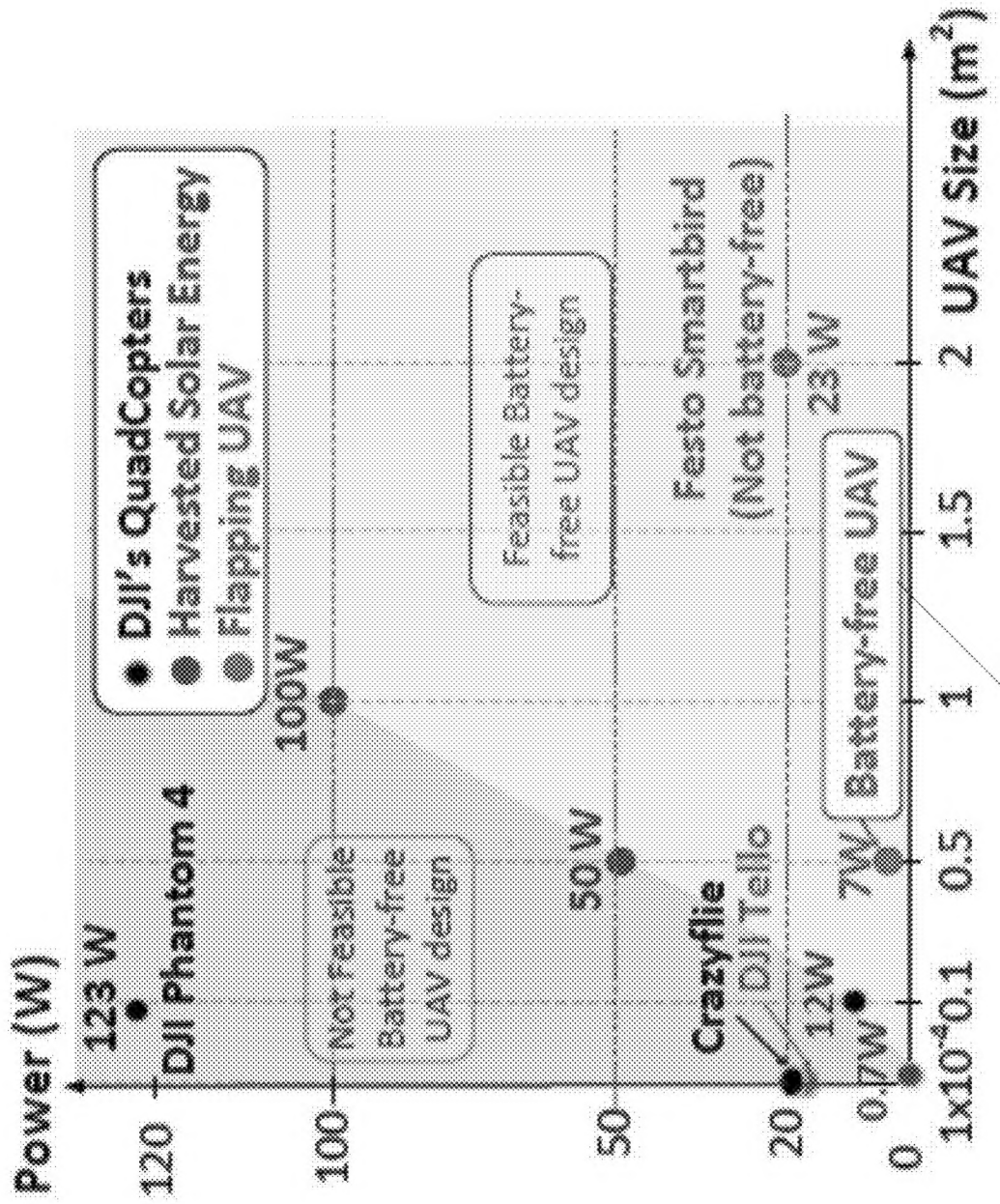

Power (W)
120
100
50
20
0
123 W
DJI Phantom 4
100W
50 W
12W
7W
0.7W
DJI's QuadCopters
Harvested Solar Energy
Flapping UAV
Not feasible Battery-free UAV design
Feasible Battery-free UAV design
Festo Smartbird (Not battery-free)
23 W
Crazyflie
DJI Tello
Battery-free UAV
1x10-4
0.1
0.5
1
1.5
2
UAV Size (m2)
10

FIG. 3

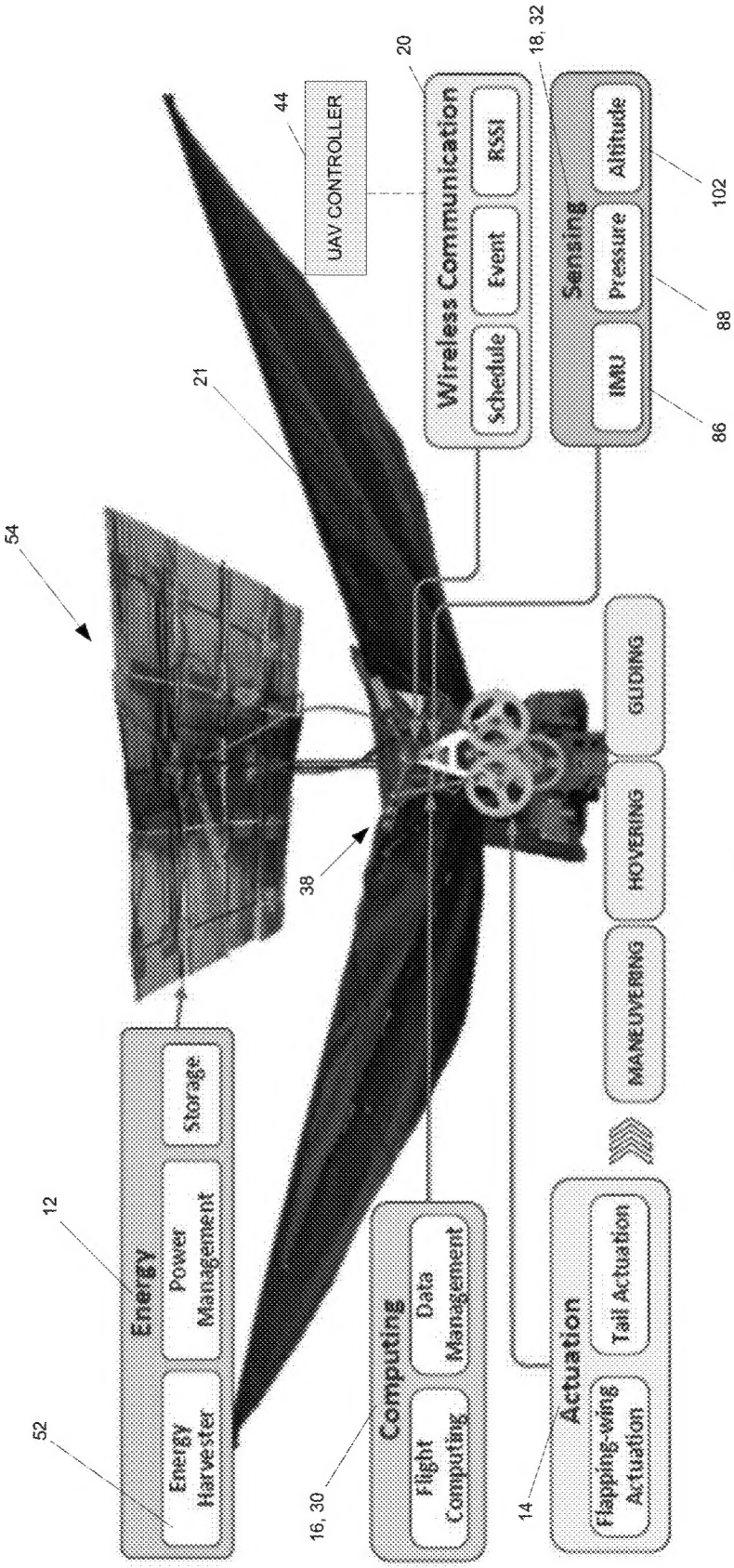

Energy
Energy Harvester
Power Management
Storage
Computing
Flight Computing
Data Management
Actuation
Flapping-wing Actuation
Tail Actuation
MANEUVERING
HOVERING
GLIDING
Wireless Communication
Schedule
Event
RSSI
Sensing
IMU
Pressure
Altitude
UAV CONTROLLER
52
12
16, 30
14
54
21
38
20
18, 32
44
86
88
102

FIG. 4

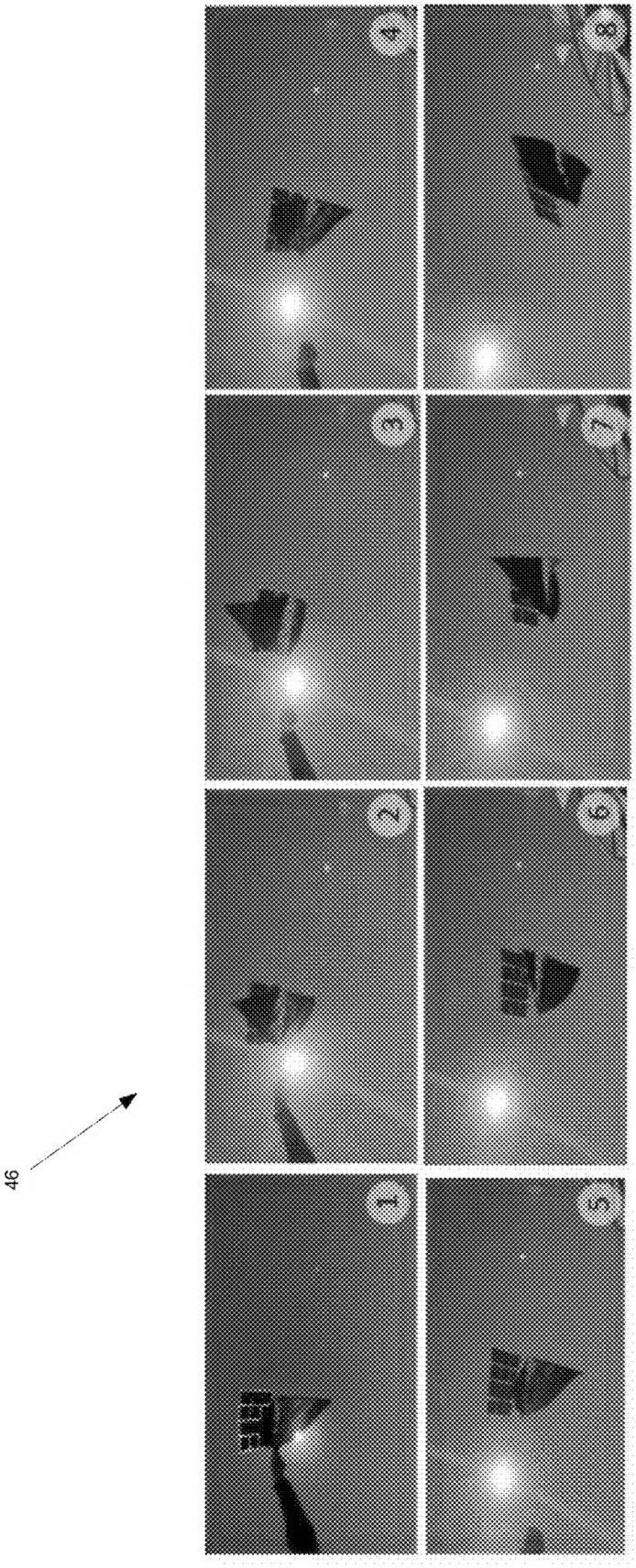


FIG. 5

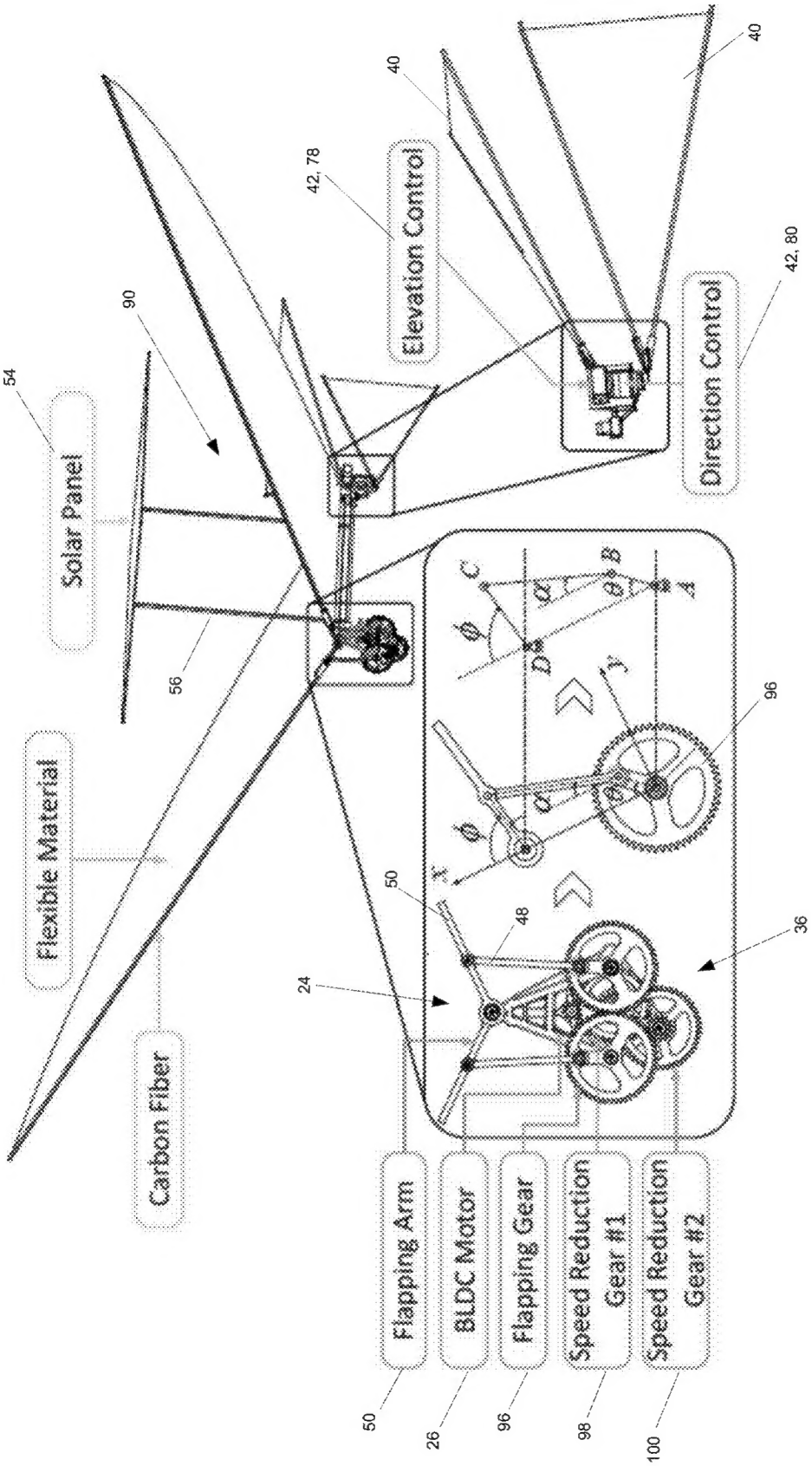

Solar Panel
Flexible Material
Carbon Fiber
Elevation Control
Direction Control
Flapping Arm
BLDC Motor
Flapping Gear
Speed Reduction Gear #1
Speed Reduction Gear #2
54
90
56
42, 78
40
42, 80
24
50
48
36
96
98
100
26

FIG. 6

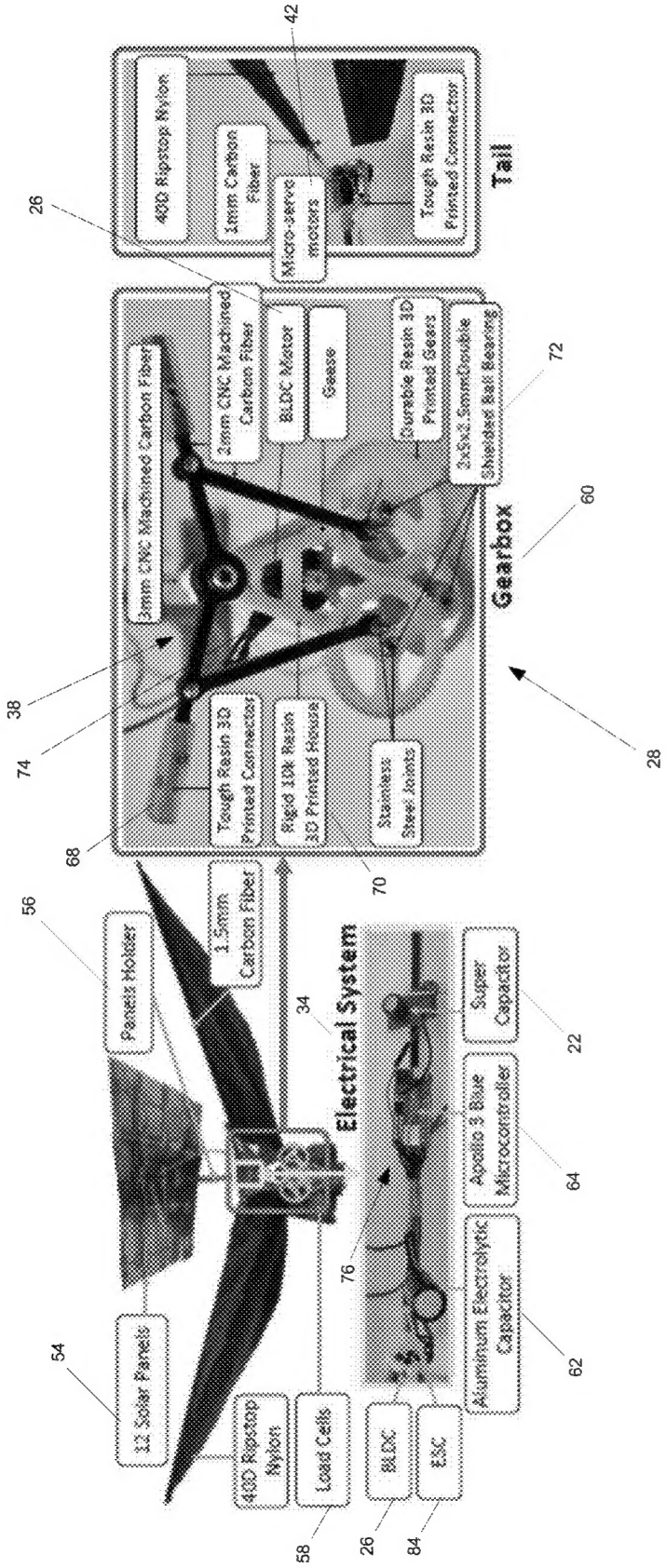

42
26
400 Ripstop Nylon
1mm Carbon Fiber
Micro-servo motors
Tough Resin 3D Printed Connector
Tail
2mm CNC Machined Carbon Fiber
BLDC Motor
Geese
Durable Resin 3D Printed Gears
2xSx2.5mmDouble Shielded Ball Bearing
72
60
Gearbox
28
38
74
68
Tough Resin 3D Printed Connector
Rigid 10k Resin 3D Printed Hinges
Stainless Steel Joints
70
56
Panels Holder
1.5mm Carbon Fiber
34
Electrical System
Super Capacitor
22
Apollo 3 Blue Microcontroller
64
76
Aluminum Electrolytic Capacitor
62
54
12 Solar Panels
400 Ripstop Nylon
Load Cells
58
BLDC
ESC
26
84

FIG. 7

Solar cell	Chemistry	Electrical			Mechanical		Efficiency	
		V	I	P	Area	Mass	P/Area	P/Mass
Ascent Bare cell [1]	CIGS	4.8	0.17	0.816	84	1	0.155	0.816
Azure multi-junction [2]	GaInP/GaAs/Ge	3.025	0.433	1.31	30.18	2	0.347	0.655
Maxeon Gen II [73]	Monocrystalline Si	0.58	6	3.48	153	6.5	0.227	0.535

FIG. 8

BATTERY-FREE UNMANNED AERIAL VEHICLE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of priority under 35 U.S.C. § 119 from U.S. Provisional Patent Application Ser. No. 63/348,182 entitled "Battery-free Unmanned Aerial Vehicle," filed on Jun. 2, 2022, the disclosure of which is hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] The present disclosure generally relates to unmanned aerial vehicles, and more specifically relates to battery-free unmanned aerial vehicles.

BACKGROUND

[0003] Drones have been promoted to be a transformative technology that will support various applications over the next decade, including, for example, military training, search and rescue, logistics, precision agriculture, and aerial photography. Also referred to as Unmanned Aerial Vehicle (UAVs) or Unmanned Aircraft Systems (UASs), UAVs can be used to gain realistic training experiences, test equipment, and tactics in preparation for missions. Many logistic companies are putting much efforts in building automatic UAV-based delivery systems. For example, pilot studies involving automatic delivery UAVs have been conducted at multiple cities around the world. As other examples, UAVs have also been proposed for use in severe conditions to chase storms, hunt hurricane, detect and monitor wildfires, and others uses. Many are also pursuing UAVs for agriculture, such as, mapping/surveying, crop-dusting/spraying, and others agricultural uses. UAVs have been also been considered for lab sample pick-up and delivery, aerial spraying, public space monitoring and guidance. Finally, drones have emerged as a promising path to conservation and sustainability, including, for example, climate change assessments and habitat monitoring.

[0004] While drone concepts are exciting, most are largely still out of reach due to short flight times, maintenance, and cost. Few drone-based technologies have been witnessed despite tons of interesting and novel concepts introduced. Short flight endurance is one of the main issues. Many traditional drones require dedicated take-off and landing spaces and do not support hovering. Vertical take-off and landing (VTOL) drones have been recently considered as they can support long-endurance (a few hours) with the ability for vertical take-off, landing, and hovering. Unfortunately, they are typically expensive, difficult to control, and require special pilot training. In addition, they are often unstable due to transitions from vertical take-off to flying because the procedure of changing propeller directions is complex and poses potential failures. Last but not least, these traditional drones are powered by LiPo batteries, and the capacities of these batteries often reduce significantly after a few weeks due to the high current discharges required during take-off and flying.

[0005] As discussed above, the trade-off between battery energy storage and weight is a main constraint for the flight times of unmanned aerial vehicles (UAV). Even for UAVs that recharge their batteries mid-flight, eventually, the batteries must be replaced. As such, there is still a desire for UAVs that can provide near-zero maintenance and long-term flight.

[0006] The description provided in the background section should not be assumed to be prior art merely because it is mentioned in or associated with the background section. The background section may include information that describes one or more aspects of the subject technology.

SUMMARY

[0007] According to certain aspects of the present disclosure, an unmanned aerial vehicle is provided. The unmanned aerial vehicle includes a four-bar linkage mechanism in mechanical communication with a pair of wings. An electrical subsystem includes an actuator in mechanical communication with the four-bar-linkage mechanism. The actuator is in electrical communication with a capacitor. A plurality of solar panels is in electrical communication with the capacitor, which is configured to harvest non-battery energy from the plurality of solar panels to power the actuator for controlling the four-bar linkage mechanism to operate the pair of wings.

[0008] According to another aspect of the present disclosure, an unmanned aerial vehicle is provided. The unmanned aerial vehicle includes a plurality of wings. An electrical subsystem is configured to control the plurality of wings. A flapping system is in mechanical association with the plurality of wings. The flapping system is in mechanical association, and in electrical communication, with the electrical subsystem. The electrical subsystem is configured to actuate the flapping system to control the plurality of wings. A plurality of solar panels is in electrical communication with the electrical subsystem. A capacitor of the electrical subsystem is configured to harvest non-battery energy from the plurality of solar panels to power the electrical subsystem for controlling the flapping system to operate the plurality of wings.

[0009] According to yet another aspect of the present disclosure, an unmanned aerial vehicle is provided. The unmanned aerial vehicle includes a four-bar linkage mechanism. A pair of wings is in mechanical communication with the four-bar-linkage mechanism. An actuator is in mechanical association with the four-bar-linkage mechanism. The actuator is in electrical communication with a capacitor. A plurality of solar panels is in electrical communication with the capacitor. The capacitor is configured to harvest non-battery energy from the plurality of solar panels to power the actuator for controlling the four-bar linkage mechanism to operate the pair of wings. A microcontroller is in electrical communication with the actuator. The microcontroller is in wireless communication with a UAV controller for controlling the actuator. At least one RC micro-servo motor is in electrical communication with the microcontroller. At least one tail is in mechanical association with the at least one RC micro-servo motor.

[0010] It is understood that other configurations of the subject technology will become readily apparent to those skilled in the art from the following detailed description, wherein various configurations of the subject technology are shown and described by way of illustration. As will be realized, the subject technology is capable of other and different configurations and its several details are capable of modification in various other respects, all without departing from the scope of the subject technology. Accordingly, the

drawings and detailed description are to be regarded as illustrative in nature and not as restrictive.

BRIEF DESCRIPTION OF DRAWINGS

[0011] The disclosure is better understood with reference to the following drawings and description. The elements in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the disclosure. Moreover, in the figures, like-referenced numerals may designate to corresponding parts throughout the different views.

[0012] FIG. **1** illustrates a battery-free unmanned aerial vehicle (UAV) according to certain aspects of the present disclosure.

[0013] FIG. **2** illustrates exemplarily applications for the battery-free UAV of FIG. **1** according to certain aspects of the present disclosure.

[0014] FIG. **3** is a chart illustrating the relationship between power consumption and size of some commercial quadcopters, flapping UAVs, and the disclosed battery-free UAV of FIG. **1**.

[0015] FIG. **4** illustrates an embodiment of a battery-free UAV according to certain aspects of the present disclosure.

[0016] FIG. **5** illustrates an example flight sequence of the battery-free UAV, according to certain aspects of the present disclosure.

[0017] FIG. **6** illustrates a four-bar-linkage flapping mechanism of a battery-free UAV, according to certain aspects of the present disclosure.

[0018] FIG. **7** illustrates components of a battery-free UAV, according to certain aspects of the present disclosure.

[0019] FIG. **8** is a chart illustrating comparisons of solar panels.

[0020] In one or more implementations, not all of the depicted components in each figure may be required, and one or more implementations may include additional components not shown in a figure. Variations in the arrangement and type of the components may be made without departing from the scope of the subject disclosure. Additional components, different components, or fewer components may be utilized within the scope of the subject disclosure.

DETAILED DESCRIPTION

[0021] The detailed description set forth below is intended as a description of various implementations and is not intended to represent the only implementations in which the subject technology may be practiced. As those skilled in the art would realize, the described implementations may be modified in various different ways, all without departing from the scope of the present disclosure. Accordingly, the drawings and description are to be regarded as illustrative in nature and not restrictive.

[0022] The disclosed technology provides a battery-free, energy harvesting, and small-sized Unmanned Aerial Vehicle (UAV). For many traditional UAVs, flight times are severely constrained due to being forced to navigate the trade-off between battery energy storage and weight. Even for traditional UAVs that recharge their batteries mid-flight, eventually, the batteries must be replaced. The disclosed technology, thus, provides improved UAVs that can survive entirely off energy harvested from the sun. As disclosed herein, these UAVs store energy momentarily in small super-capacitors before using that energy to create lift. By removing the requirement for battery recharging and replacement, these UAVs can provide extended flight times and open up new applications. Many factors significantly affect UAV performance such as, but not limited to, wing structure, UAV type, motor and harvester efficiency, environmental effects, and other factors. In certain aspects of the disclosure, the UAV is an ornithopter-like UAV with a solar rack on top and a single BLDC motor. Such an UAV could enable numerous new applications that require large-scale, sustained aircraft flight, such as, but not limited to, wildfire monitoring, smart agriculture, and urban air quality assessment.

[0023] FIG. **1** illustrates an embodiment of an UAV **10** that is, for example, an ornithopter, as in it flaps to generate lift and uses a solar rack (or parachute) to gather energy to power all operations. For example, when launched from eye height, the battery-free UAV **10** is able to stay aloft under its power.

[0024] While lithium-ion batteries are commonly used for UAV design, they are often not suitable for hazardous environments such as wildfire monitoring since the electrolyte consists of lithium salt and organic solvents, which can lead to fire hazards or explosion. More importantly, batteries add weight costs and require charging or replacement, shortening aerial time. A battery-free UAV provides the opportunity for ultra-long multi-day missions, low maintenance, and a lower ecological impact. As described in more detail below, the disclosed solar-powered UAV with low power consumption can eliminate usage of a battery and can operate entirely from the energy harvested from sunlight. By removing the battery recharging and replacement requirements, such UAVs can provide extended flight times. New applications emerge with this extended flight time, including, but not limited to, data ferrying, aerial imaging, air quality monitoring, and others. As exemplified in FIG. **2**, the battery-free UAV **10** can be a critical device for future large-scale monitoring applications that must be sustainable and have low maintenance.

[0025] In certain aspects, a 99.89 g battery-free UAV **10** with an 84 cm wingspan is provided. In such aspects, for example, the disclosed UAV **10** provides sufficient energy to flap at 4 Hz frequency with a maximum power of 3 W in daily sunlight conditions.

[0026] Compared to multi-rotors and fixed-wing UAVs, a flapping UAV is the most efficient flying mechanism that supports a reasonably large coverage area. To be specific, commercial micro multi-rotors UAVs, for example, consume roughly 20 W of power, as shown in FIG. **3**. Larger drones, for example, require more than 100 W of power to operate. Additionally, multi-rotor UAVs require a relatively high continuous electric current to actuate their motors. Without the desired current, multi-rotor UAVs cannot generate any lift and cannot control their aerial balance and stability. Flapping-wing UAVs, on the other hand, have higher efficiency compared with multi-rotor UAVs as the main lift force of multi-rotor UAVs comes from the propellers, requiring a considerable amount of power to operate compared to flapping-wing similar-sized UAVs. Subsequently, while flapping-wing and fixed-wing UAVs require similar energy since they both are able to operate with one main motor (i.e., controlling the wings in flapping UAV and rotating the main propellers in fixed-wing), flapping-wing outperforms both of them in hovering and low-speed operation performance. With reference to FIG. **3**, considering

Ascent solar BARE model, the energy required by the common quad-copter drones, state-of-the-art flapping-wing drone (Festo Smartbird), and the potential harvested energy per square meter is illustrated. As can be seen in FIG. **3**, one embodiment of a flapping UAV **10** can utilize solar power to support its operation with a size of 0.5 m^2.

[0027] The disclosed technology provides a flapping-wing UAV that can operate using the energy harvested from the environment (i.e., solar power). With reference to FIG. **4**, an embodiment of unmanned aerial vehicle (UAV) **10**, such as a Battery-free UAV system, is depicted. The battery-free UAV **10** includes five main components: (1) an Energy harvesting and management **12**, (2) an Actuation control system **14**, (3) a Computing system **16**, (4) a Sensing system **18**, and (5) a Communication system **20**. The entire UAV **10** is powered by energy harvested from a plurality of solar panels **22**, such as for example, 12 solar cells, placed on the body **90** of the UAV **10** above the wings **21**. The harvested energy is stored in at least one super-capacitor **22** in electrical communication with the plurality of. A lightweight, efficient and durable flapping system **24**, including a power transmission mechanism **28** in mechanical association with an actuator **26**, provides sufficient lift and thrust forces to fly the UAV **10**. The main computing unit **30** of the UAV **10** includes flight control and data management to collect data from the plurality of sensors **32** (i.e., IMU **86**, pressure sensors **88**, altitude sensor **102**) to flap and maneuver. In certain aspects, the UAV **10** supports Bluetooth communication allowing for remote control of the UAV **10** in real-time.

[0028] The electrical subsystem **34** (including at least the actuator **26**, the capacitor **22**, the microcontroller **64**, the aluminum electrolytic capacitor **62**, and the circuits **76**) and the mechanical flapping system **24** (including at least the power transmission mechanism **28**, the plurality of gears **36**, the four-bar linkage mechanism **38**, the coupler bar **48**, the rocker-arm **50**) are the main components of the UAV **10**. The components of the electrical subsystem **34** are in electrical communication with one another. In certain aspects, the electrical subsystem **34** of the UAV **10** utilizes, for example, a Brushless DC (BLDC) motor, as the main actuator **26** due to its efficiency, torque, and weight. The plurality of gears **36** (i.e., crank gear **94**, first speed reduction gear **98**, second speed reduction gear **100**) and the power transmission **28** then convert the rotation of the motor (i.e., the actuator **26**) to the flapping motion of the wings **21** as long as the torque relationship of the system is satisfied. A four-bar linkage mechanism **38** of the UAV **10** is designed to convert the rotational motion to flapping motion. The UAV **10** also has at least one tail **40** to balance the momentum and maneuver the flying direction. The UAV **10** includes at least one RC servo motor **42**, which are used to direct the system in Azimuth and Elevator angles. In certain aspects, the main motor (i.e., the actuator **26**) of the UAV **10** is controlled by, a microcontroller **64**, for example, an Apollo3 Blue MCU from Ambiq, which communicates wirelessly with the UAV controller **44** through Bluetooth to receive commands from the UAV controller **44** to control the actuator **26**.

[0029] The UAV **10** harvests energy from outdoor sunlight and stores energy momentarily in small super-capacitors (i.e., capacitor **22**) before using that energy to create lift via the actuator **26** controlling the flapping system **24**. FIG. **5** illustrates an example flight sequence **46** of the UAV (e.g., battery-free ornithopter).

[0030] Referring to FIG. **6**, an embodiment of the UAV **10** is illustrated. The UAV **10** includes a flapping mechanism, such as the flapping system **24**, based on the change of ϕ angle. The UAV **10** also includes the BLDC motor (i.e., the actuator **26**), the four-bar linkage mechanism **38**, a coupler bar **48**, and a flapping arm or rocker-arm **50**. Note that θ is the angular displacement of the four-bar linkage, a is the coupler bar angle, ϕ is the rocker-arm angle, and A, B, C, D are attached points of the components in the four-bar linkage mechanism **38**. By changing the angle θ using the designed BLDC motor (i.e., the actuator **26**), the flapping angle ϕ is precisely controlled. This embodiment of the UAV **10** overcomes many issues related to durability, reliability, and lightweight. As discussed in more detail below, the UAV also includes an energy harvesting device **52** of the energy harvesting and management system **12**.

[0031] The mechanical connections of the UAV **10** are on the same plane (2-D mechanism) and, therefore, allows manageable mechanical positioning and fabrication, as illustrated in FIG. **7**. The UAV **10** includes a plurality of solar panels **54**, a panel holder **56**, the pair of wings **21**, loads cells **58**, the electrical subsystem **34**, a gear box **60**, and the at least one tail **40**. In certain aspects, the plurality of solar panels **54** include 12 solar panels, but any number of solar panels is within the scope of the present disclosure. In certain aspects, the electrical subsystem **34** also includes at least an aluminum electrolytic capacitor **62**, a microcontroller **64**, and the super capacitor **22**. In certain aspects, the gearbox **60** includes a body bar **66**, a connector **68**, a house **70**, the plurality of gears **36**, the BLDC motor (i.e., the actuator **26**), and shielded ball bearings **72**. In certain aspects, the at least one tail **40** includes the least one RC micro-servo motor **42** and a motor connector **74**. In certain aspects, the house **70** can be a rigid **10***k* resin, for example, from Formlabs. The plurality of gears **36** of the UAV **10** are lightweight. In certain aspects, the body bar **66** is computed numerical controlled (CNC) machined by a 3 mm carbon fiber plate with multiple mounts for the house **70**, the at least one tail **40**, circuits **76**, and the plurality of solar panels **54**.

[0032] In certain aspects, the motor (i.e., the actuator **26**) is rated at 5Kv and weighs 5.9 grams. The motor (i.e., the actuator **26**) can work well up to 3 s (11.7V). In certain aspects, the plurality of solar panels **54** works at 4.6V; therefore, the rated speed is 4.5×5000=23, 000 rpm, equal to 383.3 Hz of flapping frequency. The gear ratio of the plurality of gears **36** is designed to reduce the flapping to 4 Hz, which needs a 96:1 reduction ratio. In certain aspects, a 70:1 reduction ratio with two reduction gears (e.g., the first speed reduction gear **98** and the second speed reduction gear **100**) is implemented instead due to the spatial constraint. In certain aspects, for example, Durable Resin from Formlabs is chosen due to the wear resistance. In certain aspects, the motor (i.e., the actuator **26**) and the gearbox **60**, which weigh 26.54 grams, work reliably for five hours without load. In certain aspects, certain components described above are manufactured with a 3D printing technique called stereolithography (SLA), which has better resolution and properties than the Extruding technique.

[0033] It is noted that: (1) The lift coefficient depends on the flexibility of the wings **21**, the materials, and also the straightness; (2) There is no evidence to optimize the wing geometry and structure; (3) The more weight on the wings, the more torque is needed to run the motor. In certain aspects, the pair of wings **21** are CNC machined carbon

fiber. In certain aspects, the wing spar of the wings **21** is 3 millimeters. In certain aspects, the pair of wings **21** include three spars as a triangular wingspan of 820 millimeters. In certain aspects, for example, 40D Ripstop Nylon makes the wings **21** sewed on the carbon fiber spars with Durable 3D Printed connections. As depicted in FIG. **6**, the at least one tail **40** includes two main direction controllers, such as an elevation controller **78** and a direction controller **80**, that allow the UAV **10** to change its elevation and direction while flying. In certain aspects, the at least one tail **40** of the battery-free UAV **10** leverages the two low-power, light-weight RC micro-servo motors **42**, such that a first RC micro-servo motor of the RC micro-servo motors **42** acts as the elevation controller **78** and a second RC micro servo motor of the RC micro-servo motors **42** acts as the direction controller **80**.

[0034] In certain aspects, the main components of the electrical subsystem **34** includes at least an electronic speed controller (ESC) **84**, the main computing unit **30**, the plurality of solar panels **54**, an Inertial Measurement Unit (IMU) **86**, and pressure sensors **88**.

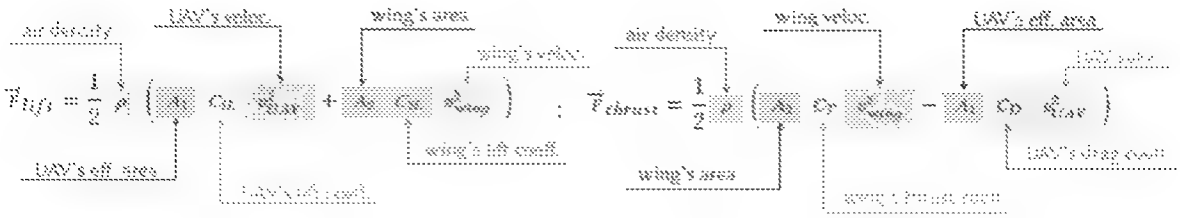
[0035] In certain aspects, the ESC **84** can work from 3V to 8V and supply up to 7 A peak and 4 A continuous and has a weight of 0.96 grams. In certain aspects, the average parasitic power draw of the ESC **84** is 32.86 mW.

[0036] The Battery-free UAV **10** is controlled by the main computing unit **30**. In certain aspects, the main computing unit **30** is, for example, a Sparkfun redboard artemis nano development board. In such aspects, the main computing unit **30** incorporates, for example, an Ambiq Apollo3 Blue microcontroller (i.e., the microcontroller **64**), which is one of the lowest power mcu available with BLE built in, although other microcontrollers are well within the scope of the present disclosure. The microcontroller **64** has 1 MB flash and 384k RAM and runs at runs at 48 MHz with a 96 MHz turbo mode and requires 6 μA/Hz. The microcontroller **64** also interfaces with a low power 6DoF IMU (LSM6DSL) and the pressure sensor **88**. The microcontroller board along with the required voltage regulation circuits have a parasitic power draw of 10.77 mW.

[0037] The weight of the plurality of solar panels **54** is dominate so the Battery-free UAV is designed to maximize power-to-mass ratio. The Table illustrated in FIG. **8** compares solar panels. While multi-junction GaInP/GaAs/Ge have the highest power-to-area ratios they are extremely fragile and expensive. Due to their fragile nature they would require a thick encapsulation to improve their durability which would further decrease its power-to-mass ratio. On the other hand Silicon cells have a significantly worse power-to-mass ratio compared with the Ascent Solar cell. In certain aspects, for example, CIGS solar cells are implemented due to having one of the best power-to-mass ratios on the market and being extremely durable and flexible, although other solar cells are well within the scope of the present disclosure. In certain aspects, the plurality of solar panels **54** are connected in a 1 s12p configuration to give a peak voltage of 4.8V and current of 1.7 A at 1000 W/m^2.

[0038] In certain aspects, the plurality of solar panels **54** are suspended on top of the body **90** of the UAV **10** using carbon fiber rods. This design improves solar panel efficiency and also improves the lift force generated by the system.

[0039] In the following discussion, the relationship between the flapping wings and the generated lift and thrust forces of the UAV **10** will be described. Due to the unsolvable and complex behaviors of fluid dynamics, the existing technique linearizes the relationship between force and flapping frequencies and other parameters and considers the average lift and drag forces over a long period. For example, the aerodynamic model of the flapping-wing UAV is composed of the aerodynamic model of the fixed-wing UAV moving in the air and the aerodynamic of flapping-wings in the static air. Thus, the lift and thrust forces of the UAV can be expressed by the coefficients as follows:


air density
UAV's velocity
wing's area
wing's velocity
air density
wing velocity
UAV's off. area
UAV's velocity
UAV's off. area
UAV's lift coeff.
wing's lift coeff.
wing's area
wing's thrust coeff.
UAV's drag coeff.

[0040] The lift force is composed of (1) the lift force contributed by the entire UAV and (2) the lift force contributed by the flapping wings. Similarly, the thrust force can also be decomposed into forces coming from the entire UAV **10**, and the wings separately. Hence, in some scenarios in which the UAV **10** (e.g., the ornithopter) has an initial velocity or the wind condition is sufficient, the required lift force for the UAV **10** is much less than usual conditions; thus, reducing the power consumption significantly. Furthermore, the solar panel rack **92** on the UAV **10** having a relatively large surface area in the positive attack angle position also greatly contributes to the entire UAV's lift force. This structure elaborates why the UAV **10** can fly with the limited harvested energy from the sun. The aerodynamics also implicitly suggests that whenever the UAV reaches a certain velocity or flies in a satisfactory wind condition, the lift force generated by the entire UAV **10** can win the gravity, and the UAV **10** can fly without making any flapping efforts. Such flying characteristics also propose the UAV's gliding mode and possibly the UAV's intermittent flapping mechanism in future work.

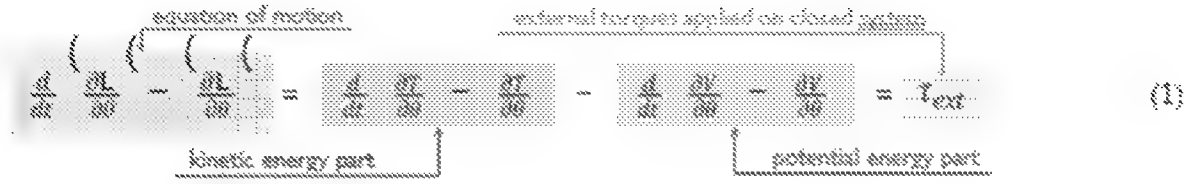
[0041] Dynamic and Kinetic (Power Transmission) Modeling. The feasibility of the battery-free UAV **10** relies not only on what we know about the aerodynamic generation procedure but also on how we comprehend the energy consumption behavior and the relationship between the energy and flapping behavior. The relationship between the energy, the motor (i.e., the actuator **26**), the power transmission mechanism **28**, and the flapping wings **21** includes (1) the positional relationship (Kinematic Modeling), (2) torque and force relationship (Dynamic Modeling), and energy behavior and consumption relationship (3) Motor Modeling.

[0042] Kinematic Modeling. In order to fly, the UAV **10** needs to transform simple harmonic motion (SHM) to reciprocation, and the four-bar linkage mechanism **38** is designed in terms of the kinematic model. The kinematic model provides a mathematical description that provides the functional dimensions, degrees of freedom, and the positional capabilities or constraints of the UAV **10**. Note that in this kinematic model, the torque generated by the motor (i.e., the actuator **26**) can be satisfied enough, whereas the force of the air applied on both wings **21** does not exceed the torque generated by the motor (i.e., the actuator **26**), and the thrust force and lift force are sufficient for the UAV **10** to fly. The four-bar linkage mechanism **28** is illustrated in FIG. **6**. As depicted in half of the four-bar linkage mechanism **28** (for ease of discussion, the other half, being a mirror version, will not be discussed), A, B, C, and D are denoted as the center A of the flapping gear or crank gear **94** of the plurality of gears **36**, the attachment point B of the coupler bar **48** to the flapping gear or crank gear **94**, the attachment point C of the coupler bar **48** to the rocker-arm **50**, and the position D of one end of the flapping arm or rocker-arm **50**, respectively. Placing the origin of coordinates system at A and knowing that A and D do not change their position over time, the relative positions of B and C with respect to A are computed as follows:

$x_B = t_1 \cdot \cos\phi$	$(x_C - x_B)^2 + (y_C - y_B)^2 = t_2^2$
$y_B = t_2 \cdot \sin\phi$	$(x_C - x_D)^2 + (y_C - y_D)^2 = t_3^2$

[0043] Solving the above system of equations with given positions of A and D and choosing the most appropriate solution for B and C based on constraints plane (see FIG. **6**), $B=(x_B, y_B)$ and $C=(x_C, y_C)$ is obtained. Simulating simple harmonic motion on θ over a time domain t with infinitesimal Δt, we transform SHM from the motor into a reciprocating movement on the rocker-arm angle, ϕ.

[0044] Dynamic Modeling. The design illustrated in FIG. **6** satisfies the assumption in Kinematic Modeling were satisfied by using dynamic modeling throughout Matlab simulations. It is noted that the dynamic model is a mathematical model that derives equations describing the relationship between forces and torques within a closed system. Lagrangian mechanics is often used to derive the relationship between the torque generated by the motor and the torque of the wings, written as $L \triangleq T - V$, where L, where is the function that describes the state of motion of the system, and T and V are the kinetic energy and potential energy of the system, respectively. Here, the equation of motion based on Lagrangian mechanics is used to establish the relationship between the wing torque and the motor torque. The equation of motion is expressed as:


equation of motion
external torques applied on closed system
kinetic energy part
potential energy part

(1)

[0045] It is noted that in other systems, the potential energy in Lagrange's equation is usually set as 0 since the four-bar linkage mechanism **38** system is in a plane that is always perpendicular to the gravitational vector; hence, potential energy does not contribute to the Lagrangian mechanics. However, in flapping-wing UAVs, there is potential energy contributing to the Lagrange's equation as the wings **21** flap continuously. More specifically, the total kinetic energy and the potential energy are calculated, respectively:

$$T = \frac{1}{2}J(?) + J(?)S(?) + J(?)S(?) + 2P(?)C(?)S(?)\ \theta(?) \tag{2}$$

(3)

$$V = mgL \cdot \sin\phi_b - 2\tan^{-}(?)\frac{2hl(?)\ \sin\theta \pm 4(l(?)l(?)\ \sin\theta)^2 - (l(?) + l(?) - l(?) + l(?) - 2l(?)h\ \cos\theta)^2 + 4(h(l(?) - l(?)\ \cos\underline{\theta}))^2}{l(?) + l(?) - l(?) + l(?) - l(?)l(?)\ \cos\theta - 2l(?)(l(?) - h\ \cos\underline{\theta})}$$

(?) indicates text missing or illegible when filed

[0046] As we can express both kinetic energy (Eq. 2) and potential energy (Eq. 3) of the system in terms of θ and θ, we can obtain the equations of motions for the subsystems (one closed system is the gear train and the four-bar linkage on the right, while another is the four-bar linkage on the left) by applying the equation of motion (Eq. 1):

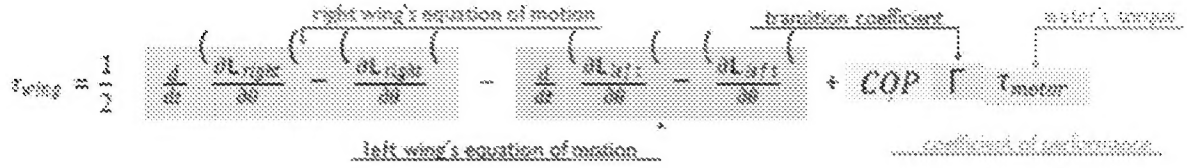
$$\frac{d}{dt} = \frac{\partial L(?)}{\partial\theta} - \frac{\partial L(?)}{\partial\theta} = \tau(?) + \tau(?) - \tau(?)(?)\ \frac{d}{dt}\frac{\partial L(?)}{\partial\theta} - \frac{\partial L(?)}{\partial\theta} = -\tau(?) + \tau(?) \tag{4}$$

(?) indicates text missing or illegible when filed

[0047] As for the torque of the motor (i.e., the actuator **26**), we establish the relationship of the torque applied on the first closed system of the UAV, τ_{input}, and the torque generated by the motor (i.e., the actuator **26**), τ_{motor}, by multiplying the transition coefficient, Γ, of 1/35 and the coefficient of performance, COP as follows:

$$\tau_{input} = \text{COP} \cdot \Gamma \cdot \tau_{motor} \tag{5}$$

[0048] Solving system of Eq. 4 with the known input torque for the four-bar linkage mechanism **38** from Eq. 5, we obtain the torque of the wings **21** with the assumption that two wings of the UAV **10** produce the same torque. Simulating the input torque with the variable τ_{input} over a time domain t, we get the formula for τ_{wing} variable as below:


right wing's equation of motion
transition coefficient
motor's torque
left wing's equation of motion
coefficient of performance

[0049] Hence, the relationship between the torque of the motor (i.e., the actuator **26**) and the torque of the wing **21** has been established.

[0050] Motor Modeling: In certain aspects, the UAV **10** utilizes the linearized BLDC model, which can be stated as below:

$$\omega = K_V \cdot V; K? = \frac{1}{K_V}: \tau = K_T \cdot I$$

? indicates text missing or illegible when filed

where K_T is the motor torque constant, K_V is the motor speed constant, I is the current, V is voltage, τ is torque, and ω is the angular velocity.

[0051] Understanding the relationship between the energy, flapping wings, and lift/thrust force established from multiple analyses mentioned above provides many insights related to the behaviors of flapping wing UAV.

[0052] In certain aspects, the UAV **10** includes a Proportional Integral Derivative (PID) control loop to stabilize the flight of the UAV **10**. In certain aspects, the UAV **10** includes a PCB with all of the electronics to reduce weight as well as parasitic losses due to resistance.

[0053] In certain aspects, the UAV **10** includes an energy-ware control method to allow the Battery-free UAV **10** to control its position, orientation and trajectory based on energy available from the environment. The energy aware control can be designed to enable the Battery-free UAV **10** to control its position, orientation and trajectory based on energy available from the environment. The energy aware control can include algorithms that steer into a direction to get more lift or thrust force from the wind or changing the orientation of the Battery-free UAV **10** to point towards the sunlight to increase energy collected.

[0054] In certain aspects, instead of solar energy, the battery-free UAV can use wind and/or vibration based energy harvesting and energy storage to optimize the system.

What is claimed is:

1. An unmanned aerial vehicle, comprising:

a four-bar linkage mechanism;

a pair of wings in mechanical communication with the four-bar-linkage mechanism;

an electrical subsystem comprising an actuator in mechanical communication with the four-bar-linkage mechanism, the actuator in electrical communication with a capacitor; and

a plurality of solar panels in electrical communication with the capacitor, wherein the capacitor is configured to harvest non-battery energy from the plurality of solar panels to power the actuator for controlling the four-bar linkage mechanism to operate the pair of wings.

2. The unmanned aerial vehicle of claim **1**, further comprising at least one tail in electrical communication with the electrical subsystem.

3. The unmanned aerial vehicle of claim **2**, further comprising at least one RC micro-servo motor in mechanical communication with the at least one tail and in electrical communication with the electrical subsystem.

4. The unmanned aerial vehicle of claim **3**, wherein the at least one RC micro-servo motor comprises a first RC micro-servo motor configured to control elevation and a second RC micro-servo moto configured to control direction.

5. The unmanned aerial vehicle of claim **4**, further comprising a microcontroller in electrical communication with the actuator and the at least one RC micro-servo motor, wherein the microcontroller is in wireless communication with a UAV controller for controlling the actuator and the at least one RC micro-servo motor.

6. The unmanned aerial vehicle of claim **5**, further comprising a plurality of sensors in electrical communication with the microcontroller, wherein the plurality of sensors comprises one of an inertial measurement unit, a pressure sensor, and an altitude sensor.

7. The unmanned aerial vehicle of claim **6**, further comprising an electronic speed controller in electrical communication with the microcontroller.

8. The unmanned aerial vehicle of claim **1**, wherein the four-bar-linkage mechanism includes one degree of freedom.

9. An unmanned aerial vehicle, comprising:

a plurality of wings;

an electrical subsystem configured to control the plurality of wings;

a flapping system in mechanical association with the plurality of wings, wherein the flapping system is in mechanical association, and in electrical communication, with the electrical subsystem, wherein the electrical subsystem is configured to actuate the flapping system to control the plurality of wings; and

a plurality of solar panels in electrical communication with the electrical subsystem, wherein a capacitor of the electrical subsystem is configured to harvest non-battery energy from the plurality of solar panels to power the electrical subsystem for controlling the flapping system to operate the plurality of wings.

10. The unmanned aerial vehicle of claim **9**, further comprising at least one tail in electrical communication with the electrical subsystem.

11. The unmanned aerial vehicle of claim **10**, further comprising at least one RC micro-servo motor in mechanical communication with the at least one tail and in electrical communication with the electrical subsystem.

12. The unmanned aerial vehicle of claim **11**, wherein the at least one RC micro-servo motor comprises a first RC micro-servo motor configured to control elevation and a second RC micro-servo moto configured to control direction.

13. The unmanned aerial vehicle of claim **12**, wherein the electrical subsystem comprises a microcontroller, wherein the microcontroller is in wireless communication with a UAV controller for controlling the flapping system.

14. The unmanned aerial vehicle of claim **13**, further comprising a plurality of sensors in electrical communication with the microcontroller, wherein the plurality of sensors comprises one of an inertial measurement unit, a pressure sensor, and an altitude sensor.

15. The unmanned aerial vehicle of claim **14**, further comprising an electronic speed controller in electrical communication with the microcontroller.

16. An unmanned aerial vehicle, comprising:

a four-bar linkage mechanism;

a pair of wings in mechanical communication with the four-bar-linkage mechanism;

an actuator in mechanical association with the four-bar-linkage mechanism, the actuator in electrical communication with a capacitor;

a plurality of solar panels in electrical communication with the capacitor, wherein the capacitor is configured to harvest non-battery energy from the plurality of solar panels to power the actuator for controlling the four-bar linkage mechanism to operate the pair of wings;

a microcontroller in electrical communication with the actuator, wherein the microcontroller is in wireless communication with a UAV controller for controlling the actuator;

at least one RC micro-servo motor in electrical communication with the microcontroller; and

at least one tail in mechanical association with the at least one RC micro-servo motor.

17. The unmanned aerial vehicle of claim **16**, wherein the at least one RC micro-servo motor comprises a first RC micro-servo motor configured to control elevation and a second RC micro-servo moto configured to control direction.

18. The unmanned aerial vehicle of claim **16**, further comprising a plurality of sensors in electrical communication with the microcontroller, wherein the plurality of sensors comprises one of an inertial measurement unit, a pressure sensor, and an altitude sensor.

19. The unmanned aerial vehicle of claim **16**, further comprising an electronic speed controller in electrical communication with the microcontroller.

20. The unmanned aerial vehicle of claim **16**, wherein the plurality of solar panels comprises 12 solar cells.

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